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The effect of the physical boundary conditions on the thermal performance of molten salt thermocline tank

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ABSTRACT

Methods of solving some of the critical design consideration associated with the thermocline storage system with unusual physical boundary conditions bring new problems: the effect of insert liner should not be ignored with small solid filler size, and it is hard to take advantage of truncated cone shaped tank for decreasing the potential of thermal ratcheting and increasing the maximum height of the tank, both while maintaining a good efficiency.

In this study, a transient two-dimensional and two-temperature model is developed to investigate the heat transfer and fluid dynamics in a molten salt thermocline thermal storage system. After model validation, the effects of physical boundary conditions including insert liner and sloped wall on the thermal performance of thermocline storage system is investigated through the entropy generation analysis.

The results show that both of the axial and radial convex size of the liner should be as small as possible, resulting in smaller average velocity and less disturbance in the flow. The truncated cone shaped tank has an advantage in the charging process with low entropy generation in molten salt and solid material, while it goes against the discharging process. It is found that larger inclined angle of the sloped wall causes smaller thermocline thickness and entropy generation with the same tank height and tank volume for truncated cone shaped tanks. Besides, larger tank height is better for the truncated cone shaped tanks with the same tank volume.

1. Introduction

Among the various utility scale renewable energy technologies, concentrated solar power (CSP) has been identified as a promising and emerging renewable energy technology with the ability to store energy as high temperature heat and continue producing power when solar energy is not available. The integration of solar thermal energy storage (TES) is a viable means to enhance dispatchability, increase the value of concentrated solar energy and make the plant more reliable.

A number of viable candidates for TES systems that might be applied on a commercial scale for CSP plants have been investigated in the literature, usually including three types: sensible, latent and thermochemical, among which sensible heat storage has tremendous preponderance over other thermal storage mechanisms due to its low cost and design simplicity.

Sensible heat storage using molten salt as the storage medium and direct heat transfer fluid can offer the best balance of capacity, cost, efficiency and usability at high temperatures [1], so molten salt sensible heat TES system are widely applied presently [2], especially the two-tank system.

The two-tank system has a high-temperature tank and a low-temperature tank for storing molten salt. It is the most mature utility-scale thermal energy storage (TES) system for CSP plants, and has been applied or projected in many CSP plants. However, the two-tank molten salt TES system has very limited space for cost reduction.

The single-tank thermocline (STTC) TES system has only one storage tank and would use molten salt as the direct heat transfer fluid, storing energy gathered in the solar field, and transferring

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Nomenclature

a, b, c, d	axial and radial size of the insert liner, m
C_p	specific heat capacity, J/kg K
D	diameter of the tank, m
$\vec{e_r}, \vec{e_x}$	unit vector in the r and x direction, respectively
Ex	exergy, W
F	inertial coefficient
g	acceleration due to gravity, m/s^2
H	tank height, m
h_i	interstitial heat transfer coefficient, W/m^3 K
K	permeability of porous material, m^2
k	thermal conductivity, W/m K
l	length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
P	thermal power, W
p	pressure, Pa
Pr	Prandtl number
Q	heat, J
Re	Reynolds number
$\dot{S}'''$	Entropy generation rate per unit volume, W/m^3 K
T	temperature, K
t	time, s
v	velocity, m/s

Greek symbols

ε	porosity of packed-bed region
η	efficiency
μ	viscosity, kg/m s
ρ	density, kg/m^3

Subscripts

Air	air
crit	critical value
c	cold fluid
dc	discharging
eff	effective value
gen,l	liquid entropy generation
gen,s	solid entropy generation
h	hot fluid
i	insulation layers or tank steel
in	inlet
l	length, liquid material
out	outlet
s	solid material
st	steel wall
store	energy stored

that energy when needed. With the hot and cold fluid in a single tank, the thermocline storage system relies on thermal buoyancy to maintain thermal stratification and discrete high- and low-temperature regions of the TES system. A low-cost solid filler used to pack the single storage tank acts as the primary thermal storage medium and reduces the overall required quantities of the relatively higher cost molten salt heat transfer fluid, which is usually a “packed-bed” of aggregate and sand [1]. As thus the STTC provides a more cost-effective option for TES systems with a potential cost reduction of 20%–37% compared to the two-tank system [2].

Since the advantage of cost reduction, the STTC TES system is progressively becoming an important research topic. A small pilot-scale packed-bed molten salt thermocline system has been successfully demonstrated in Sandia National Laboratories [3]. M.M. Valmiki et al. [4] presents an experimental study of the energy charge and discharge processes in a small oil packed bed thermocline thermal storage tank.

Some research efforts have led to the development of nitrate salt mixtures with low melting temperatures and high thermal stabilities for CSP applications [5]. Solid materials for high temperature thermal energy storage system in CSP have also been widely investigated [6].

Yang and Garimella [7,8] carried out a series of numerical investigations on the molten-salt packed-bed thermocline system using the developed two-temperature model. Li et al. [9] presented dimensionless heat transfer governing equations for fluid and solid fillers for the packed-bed thermocline TES and studied various scenarios of thermal energy charging and discharging processes. Xu et al. [1,10,11] presented a transient two-dimensional dispersion-concentric model to investigate the discharging behavior of the packed-bed thermocline tank. A parametric analysis was carried out and various influencing factors were analyzed. Different one-dimensional models were also proposed [12–15]. Mario Biencinto [16] developed a simulation model for solar thermal power plants with a thermocline storage tank with logistic function in TRNSYS, and assessed different operation strategies.

Entropy generation and exergy transport were monitored to investigate the influence of internal granule diameter and external convection losses on tank performance [17]. External convection losses strongly influence entropy generation inside the tank fillerbed due to the development of radial temperature gradients and increased irreversible thermal diffusion. The analysis in Ref. [18] showed that, for packed beds, sensible heat storage systems can provide much higher exergy recovery as compared to phase change material storage systems under similar high temperature storage conditions.

2. General considerations and description of the study

Though a lot of research efforts have been focused on the STTC TES system, most of the above studies were focused on evaluating the thermal performance of cylindrical type tank without insert liner. In practical some of the critical design consideration and the inherent flaws associated with the STTC TES system need to be solved:1) the high temperature and corrosion of the molten salt, 2) the limited height of the tank, 3) the thermal ratcheting of tank's wall. These would cause different physical boundary conditions with former research.

The first problem can be solved by the complicated wall of the thermocline tank. The single-tank thermocline (STTC) tank used in CSP plants at an industrial scale usually has a “sandwich configuration” side wall construction consisting of multiple layers [7,19–21]: an inner firebrick layer for thermal isolation, a steel shell layer for mechanical support and an outer layer for corrosion protection and thermal insulation. To inhibit leakage and corrosion of molten salt through the internal insulation, an incoloy or AISI 321H stainless steel insert liner is installed between the rock packed bed and insulation, which is corrugated in both the horizontal and longitudinal directions to accommodate thermal expansion and